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RESEARCH ON ELECTROPHYSICAL CHARACTERISTICS OF PLASMA ARC IN CO2

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ABSTRACT

A brief analytical review of research papers on the processes of arc welding was made. Conclusion on the relevance of the research in the field of synthesis of welding process control systems and the use of automatic systems was made. To implement the control processes, empirical studies of the current-voltage characteristics of the arc were performed to determine the parameters that could be considered as the parameters of the automatic control system. The experiments were performed to study the current-voltage characteristics of a compressed plasma-arc when C02 is used as plasma gas. Different torch schemes were used in the experiments. Forms of the current-voltage characteristics were examined. A conclusion was made that the parameters to control the welding process should be carried out with respect to a set of parameters, i.e. it should be vectorial. Accurate analytical models of welding processes are impossible to obtain, therefore, the methods of the fuzzy set theory are used, the decision models and the theory of possibilities that should be applied to formalize the welding parameters and the construction of the control system should be performed in the form of a hybrid control system.

***KEYWORDS**: Plasma-Arc Welding, Control System, Current-Voltage Characteristic Shielding Gas, Torch Schemes, Plasma-Arc & Probing*

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Original Article

1. INTRODUCTION

In the process of manufacture of large-size metal structures, the use of welding takes place largely. It is possible to reduce the production time with the use of automation equipment. If welding is done manually, it takes a lot of time, but with the use of welding machines, the production time can be reduced. In such a way, the task of automatic control of welding processes remains relevant. It should be noted that use of plasma arc welding is a promising trend. The plasma arc welding has been used for a fairly long time. It is necessary to establish systems of automatic control of plasma arc welding processes. Availability of automatic control systems allows establishing robots that will perform welding with the use of this method.

The system of automatic control consists of a controlled object and a controller. The controlled object is the plasma arc welding process. The controller has to be established. The controller establishment is done relatively easy if you have an adequate mathematical model of the controlled object. In addition, the controller can be established based on acceleration characteristics. Arc control of the plasma arc welding can be referred to complex processes. It is impossible to get an adequate mathematical model for the plasma arc welding process

that is the model that will depict the welding process fairly and accurately. This may be due to the fact that arc of the plasma arc welding results from a combustion process, while the combustion processes do not have accurate mathematical formulation. In this way, it is impossible to establish an accurate controller of the automatic control system based on a mathematical model. Therefore, it is possible to synthetically produce the controller based on the acceleration characteristic. The acceleration characteristic shows graphical dependence between the input parameter of the controlled object and the output parameter. Therefore, for the plasma arc welding it is possible to use volt-ampere characteristics or other electrophysical characteristics in the form of acceleration characteristics through the form of which, it is possible to synthesize adequate controllers.

This way, the first problem that should be solved in order to establish the systems of the automatic control of the plasma arc welding is the task of researching volt-ampere characteristics, electric field intensity and radial dimensions of the plasma arc. In order to solve this problem, it is necessary to perform experiments, obtain the experiment results and process these results. This is the objective of the present article, because the obtained and processed experimental results shall become basis for further solution of the problem of synthesizing automatic control of the plasma arc welding.

A lot of research papers consider the technology of welding processes, equipment of welding and the control systems of regulating the welding parameters.

The paper [1] presents the principles of plasma-arc welding and an overview of recent researches and applications in this area. Two modes of plasma-arc welding (melt and keyhole) are described, the influence factors are analyzed and three-dimensional modeling is made. Plasma-arc welding process model and process of a controlled pulsing keyhole device and system for welding control has been offered.

In [2] a variant of improving the plasma welding process efficiency using narrowed arcs has been offered. The paper is an overview and examination of the variants of the plasma-arc welding process, the latest advances in probing, control, and numerical modeling of the plasma-arc keyhole process. The paper also presents the arc control system.

The paper [3] presents the methods of probing, controlling the process of plasma welding and explains the use of a highly constricted arc, in order to obtain keyhole inside the molten pool. The paper is a critical overview of the plasma welding process. In [4] the researches, distribution of the electrical properties of the welding plasma-arc by applying a new method of double active probes. The results of the study are useful in developing and optimizing the parameters of a plasma-arc source, such as a transverse arc and a coupling arc.

The paper [5] presents the results of the study on the arc plasma shape and spectral characteristics by the implementation of laser welding, as pulsed arc welding. The conductive mechanism of arc ignition by laser hybrid welding was researched, and it has been discovered that the plasma current moves into the arc anode under the action of the electrical field. The calculation results of the plasma resistivity indicate that the laser plasma has a low resistivity as the starting point, for the formation of conducting channels. If the duration of the laser pulse increases, the intensity of the plasma emission spectrum and plasma electron density will also increase, and the arc temperature will decrease.

The automatic control system can be established for any welding process, and not only for the plasma arc welding. Independently of the welding method, the method of the control system development shall run under conditions of uncertainty, with regard to the analytical model of the controlled object. The controller shall be designed based on the acceleration characteristic.

The welding process control system is implemented on the classical principle of the automatic control system synthesis [6] or with the use of direct control methods, i.e. without feedback coupling or the feedback coupling control. The structure of the closed-loop control system is shown in figure 1.

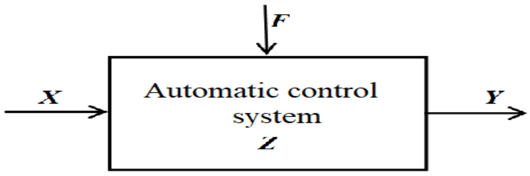

Figure 1: The General Structure of the Automatic Control System: X - Vector of Control Actions; Z - States Vector; F - Disturbance Vector; Y - Vector of Output Parameters.

As follows from the research paper [6], welding automatic control systems can be implemented using deviation, state or complex control. In accordance with the classical theory of automatic control, the state control is often defined as the derived functions of y output quantity. As for the welding process due to numerous disturbances and difficulty of the welding arc modeling and the whole welding process, it is difficult to determine the states in the form of differential equations.

In this paper, we propose for consideration conditions of the plasma arc welding process as a controlled object based on analysis of experimental research results, which will let us get acceleration characteristics for further development of the control system, under conditions of uncertainty.

2. EMPIRICAL STUDIES ON THE CURRENT-VOLTAGE CHARACTERISTICS OF THE ARC

Let us consider which parameters can be accepted to determine the state of the control system. The control in the process of welding is implemented within the system “arc - power source”. The stability of this system is determined by the type of the external current-voltage characteristics.

The type of the current-voltage characteristic of the arc significantly depends on the processes in the arc, it is determined by the change of electrode voltage drop Uк, Ua, as well as by the electric field intensity of the arc column [7]. There is a relationship between the magnitude of the voltage drop and the length of the arc discharge, which is defined by the following formula:

$$U_{Д} = U_{к} + U_{a} + \int_{0}^{L} E(l)dl \qquad (1)$$

Where, Uк is the voltage drop at the cathode (V); Ua is the voltage drop at the anode; E is the electric field intensity in the arc column (V/m); L is the arc length (m); l is the current coordinate of the arc length (m).

Composition of the plasma gas significantly affects the plasma arc parameters: heat flux density, plasma-forming gas flow rate and other parameters that determine the technological properties of the welding process. Welding environment is a plasma-forming gas (protective gas), metallic fumes: $CO_2 \rightarrow C+O_2$; $C \rightarrow C^{+}+C^{-}$; $O_2 \rightarrow O+O$; $O \rightarrow O^{+}+O^{-}$.

The electric field intensity and current-voltage characteristics of the arc column are influenced by the coefficient of the thermal conductivity of the gas. When the coefficient increases, the voltage gradient in the arc column also increases. It is connected with the increase in the heat, which transfers between the arc column, the environment and contraction of the arc and obtaining the cylindrical shape of the arc [7 – 11].

It has been a while [12] was published, that explains the voltage of a constricted arc in argon increases with the growth of current and plasma gas flow, as well as with the dependence on electrode into the nozzle and decreasing the diameter of the nozzle passage. The type of the static current-voltage characteristic for the arc is rising, that is connected with the increase of the sum of Uк and Ua. It is significant that the increase of the electric field intensity in an arc column is not the main reason for a rising branch of the current-voltage characteristic of the plasma-arc in argon [10].

The composition of the shielding gas also affects the arc voltage and the dielectric field intensity in the welding environment. When applying argon as a shielding gas or carbon dioxide, the voltage drop will be less than in the process of welding with air and nitrogen, at the same arc length [10 – 12]. This is rather obvious, since the shielding gases have different thermophysical properties.

The experiments were conducted to study the current-voltage characteristics of the constricted plasma-arc when C02 is used as a plasma gas.A copper water-cooled anode was used to improve the accuracy of the arc length fixing in the experimental determination of current-voltage characteristics. The welding process should be at a speed that prevents the penetration of the anode, and to prevent emerging the hidden component of the arc length. Figure 2 shows different torch schemes that were used to conduct the experiments.

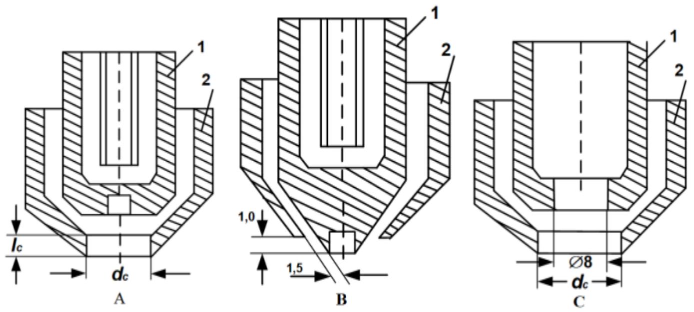

Figure 2: Schemes of Torches to Generation of Plasma (A, C) and Stabilized Arc (B) 1 - Electrode with Hafnium Insert (A, B) and Ring Insert (C); 2 - Molding Nozzle (L_c - Nozzle Length, D_c - Nozzle Diameter).

Different torch schemes were used in the experiments; scheme of plasma welding process with a filler wire was used: when the filler wire was melted in the arc column, the end of the filler wire was short-circuited to the weld pool (Figure 3).

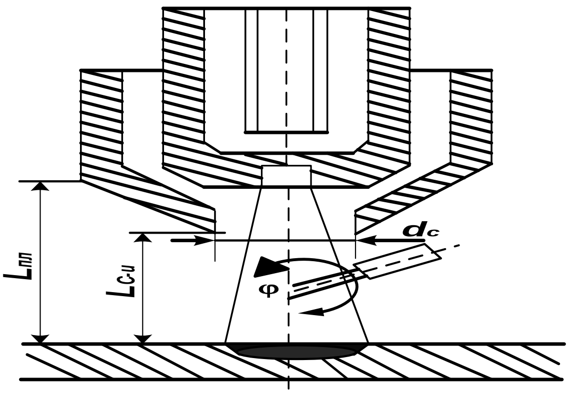

Figure 3: Scheme of the Plasma Welding Process in $C0_2$.

A rectifier from the УПС-804 УХЛ4 (an equipment for processing plasma) installation for plasma welding was used as a power source [13].

As a result of the conducted experiments, the current-voltage characteristics of the plasma-arc with CO2 plasma gas, current range of 60–400 A were obtained for various values of gas flow (gпл.г), nozzle diameter (dc), plasma-arc length (Lпл), concentration ratio, torch construction, polarity, as well as for different schemes of the process with the use of thermochemical cathode.As a result of the conducted experiments, the current-voltage characteristics of the plasma-arc in CO2 were obtained at various values of the plasma gas flow and the diameter of the molding nozzle (Figure 4).

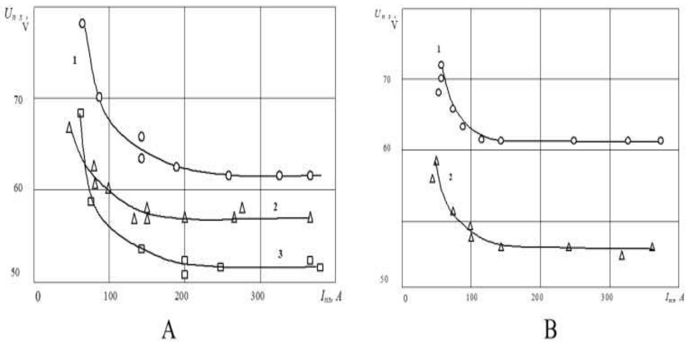

Figure 4: Current-Voltage Characteristics of the Plasma-Arc In CO_2 At Various Values: A - Plasma Gas Flow 1 - $G_{пл.Г}$ 0.2 G/S; 2 - $G_{пл.Г}$. 0.4 G/S (D_c = 8 Mm, $L_{пл}$ = 28 Mm, L_c = 5mm); B - Diameter Of The Molding Nozzle: 1 - D_c = 8 Mm, 2 - D_c = 6 Mm ($L_{пл}$= 28 Mm, L_c = 5mm, $G_{пл.Г}$ 0.2 G/S).

Figure 5 shows the current-voltage characteristics of the plasma-arc in *$C0_2$* at various values of the arc length and nozzle length. Figure 6 shows the current-voltage characteristics of the plasma-arc in *$C0_2$* depending on the torch construction and the scheme of the welding process.

According to Figures 4–6 which indicates that at currents less than 100 A, the arc voltage significantly depends on the current, and the current-voltage characteristic of the arc has a dropping section.

With the increase of the current, the current-voltage characteristic of the arc transforms into a linear (stiff) dependence, which is much easier realized when using automatic control.

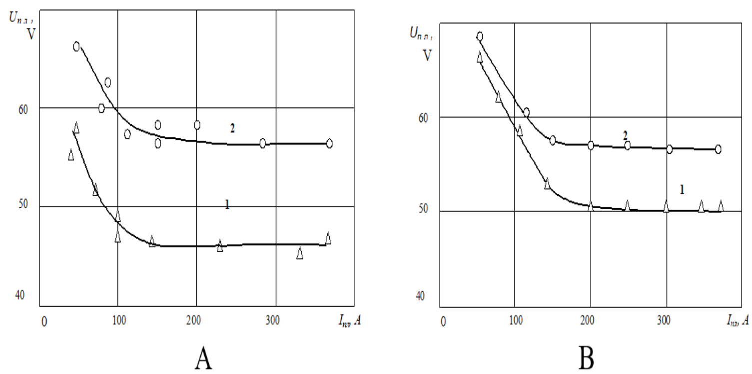

Figure 5: Current-Voltage Characteristics of the Plasma-Arc in $C0_2$ At Various Values: A - Arc Length: 1 - $L_{пл}$= 18 Mm; 2 - $L_{пл}$ = 28 Mm (D_c = 8 Mm, L_c = 5mm, $G_{пл.Г}$0.2 G/S; B - Nozzle Length: 1 - L_c = 0.5mm; 2 - L_c = 6mm (D_c = 8 Mm, $L_{пл}$ = 15 Mm, $G_{пл.Г}$ 0.33 G/S).

If the plasma gas flow increases (Figure 4A) and reducing the nozzle diameter (Figure 4B), as well as the extension of the length of the nozzle passage (Figure 5B), the arc voltage increases, which is determined by the increase in the electric field intensity in the column.

It was concluded that by increasing the intensity of the arc compression in the plasma nozzle, the voltage will increase and at lower current, the current-voltage characteristic of the arc becomes linear. The voltage increases by the increasing of the length of the arc plasma (Figure 5A).

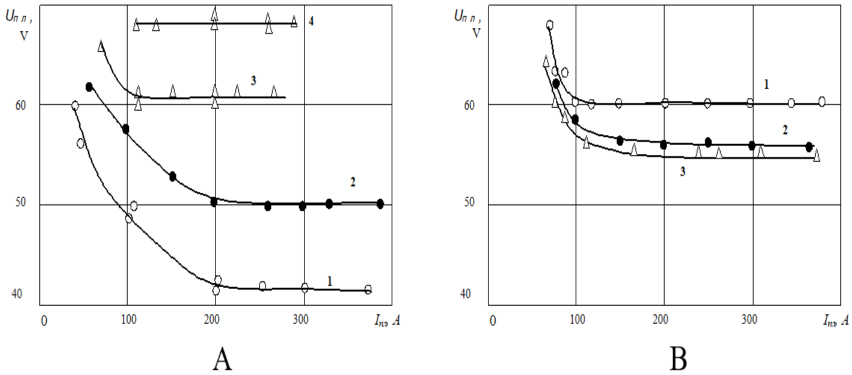

Figure 6: Current-Voltage Characteristics of the Plasma-Arc in $C0_2$: A) Torch Construction: 1, 2 - Torch for Stabilized Arc, 1 - $L_{пл}$= 15 Mm, 2 - $L_{пл}$= 20mm (D_c = 8 Mm, Mpl 0.33 G/S): 3, 4 - Torch With Orifice Anode: 3 - $L_{пл}$ = 20 Mm, 4 - $L_{пл}$ = 25mm. (D_c = 11.5 Mm, $L_{пл}$ = 15 Mm, L_a = 25mm, D_a = 10mm, $G_{пл.Г}$= 0.33 G/S); B) Welding Process Schemes: 1, 3 - With Filler Wire: 1 - $L_{пр-И}$= 7mm, 3 - $L_{пр-И}$= 0; 2 - Without Filler Wire (D_c = 8 Mm, $L_{пл}$ = 15 Mm, L_c= 6mm, $G_{пл.Г}$= 0.33 G/S).

A torch was used to obtain a stabilized arc, as in [14] (Figure 1), (Figure 6A) shows that in the current-voltage characteristic of a stabilized arc, there is a transition from a nonlinear (dropping) section to a linear section in the region of heavy currents. Using torchers with an orifice anode with current less than 100 A, causes falling section in the arc current-voltage characteristic, and at a current above 100 A, it will give a linear section. The arc current-voltage characteristic is influenced by the process of plasma welding (Figure 6B). If filler wire was applied and it's melting in the plasma arc, the arc voltage increases. This process can be explained by the cooling effect of the metaled vapor of the wire. (Figure 6B) shows a slight decrease in the arc voltage, when the filler wire melts in the weld pool. This result from the fact that the discharge spot passes from a product to a wire and the arc length is reduced.

3. STUDIES WITH THE USE OF PLASMA-ARC PROBING

Further experiments were conducted to study the causes of changes in the voltage of the plasma discharge, depending on the parameters of the mode and process schemes using plasma-arc probing.The studies were carried out according to the method of cross probing [15], that allowed to obtain the graphical dependences of the arc column electric field intensity, electrode voltage drops and arc column radial dimensions from mode parameters using different torch constructions and welding process scheme.

Probing is performed by two double rotating probes which cross the arc column. The installation scheme for plasma-arc probing is shown in (Figure 7). The probe 7 - tungsten wire with a diameter of (0.2×10^{-3}m) in a quartz tube with an outer diameter of (1.3×10^{-3} m). The probe is placed in a porcelain guide (6) with two holes, mounted on the shaft of the reducer (5). Angular rotation speed of the probes- 2.9 rad/s, linear speed - 0.492 m/s.

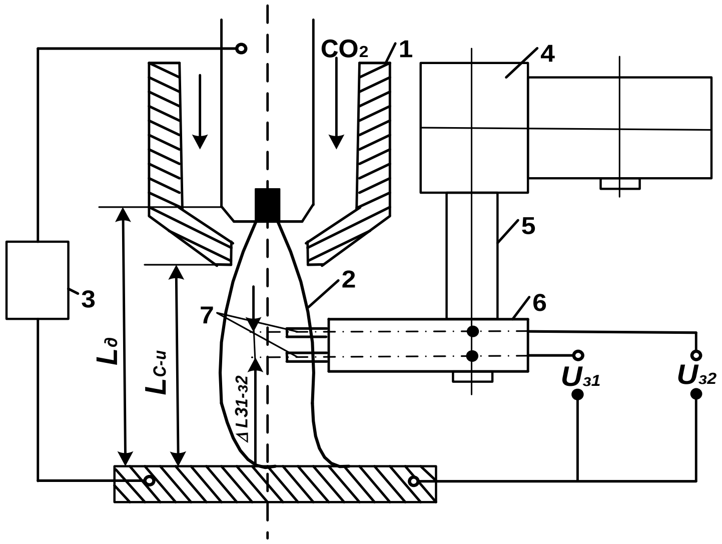

Figure 7: Installation Scheme for Plasma-Arc Probing: 2 - Plasmatron, 2 - Plasma-Arc, 3 – Power Source, 4 - Reducer With Electric Motor, 5 - Reducer Shaft, 6 - Porcelain Tube, 7 – Probes.

The probes are installed in the way that their ends cross the axis of the arc. The potentials of the probes relative to the product and the total arc voltage Uд were recorded during the experiments.Figure.8 shows the arc probing schemes and corresponding oscillographs. Figure 9 shows a scheme for determining the electric field intensity and the diameter of the arc column.The values E, Ua, Uк, dст could be found when processing the oscillographs (Figure 9). The value E is calculated by the formula:

$$E = \frac{U_{з1} - U_{з2}}{\Delta L_{з1-з2}} \tag{2}$$

Where, E is the electric field intensity, V/m; Uз1, Uз2 - potentials of the first and the second probes, measured oscillographs, V; ΔLз1–з2 - distance between the probes, m; Δlз1-з2 = 3x10–3 m.

The voltages Ua, Uк were determined by extrapolation of the dependence Uд=f(Lпл) under the direct and inversed polarity of the plasma-arc.

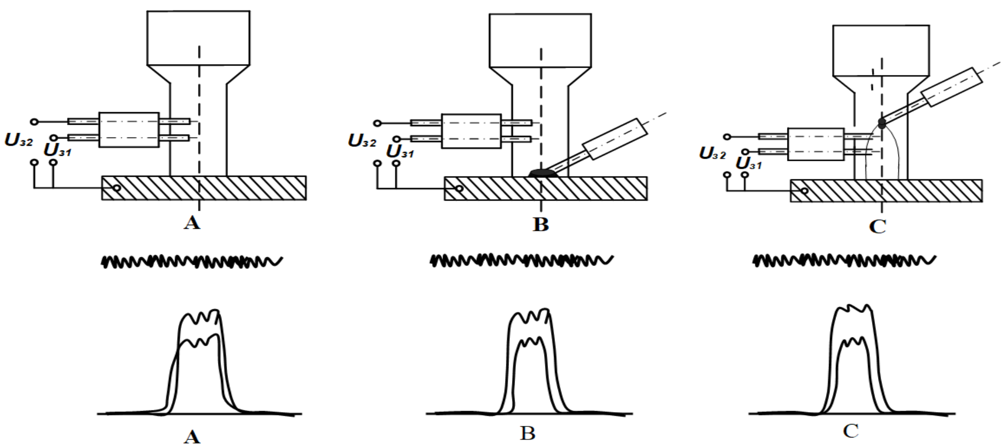

Figure 8: Arc Probing Schemes With Double Rotating Probes and Corresponding Oscillographs: A) Without Filler Wire; B) Over the Wire (Lпр-И=0); C) Under the Wire.

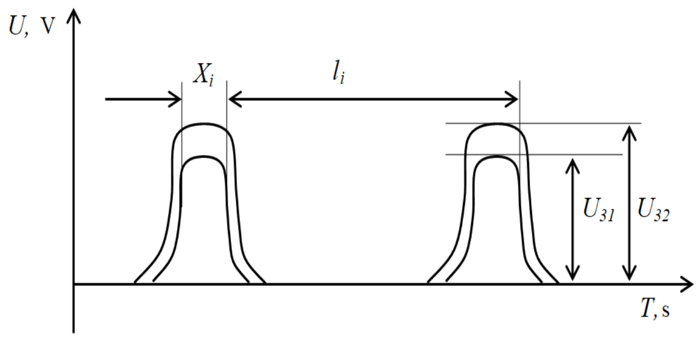

Figure 9: Scheme for Determining the Electric Field Intensity and the Diameter of the Arc Column.

The diameter of the arc column was calculated by the formula:

$$d_{cm} = 2\pi R \frac{x_i}{l_i} \tag{3}$$

Where, dcт is the diameter of the plasma-arc column, m; R is the distance between the rotation axis of the probe and the axis of the arc column, m; xi is the length of the probing impulse on the oscillograph (Figure 9), m; li is the distance between probing impulses on the oscillograph see (Figure 9), m.

Figure.10 shows the obtained dependence of the electric field intensity of the arc column on the current for the plasma and stabilized arc.

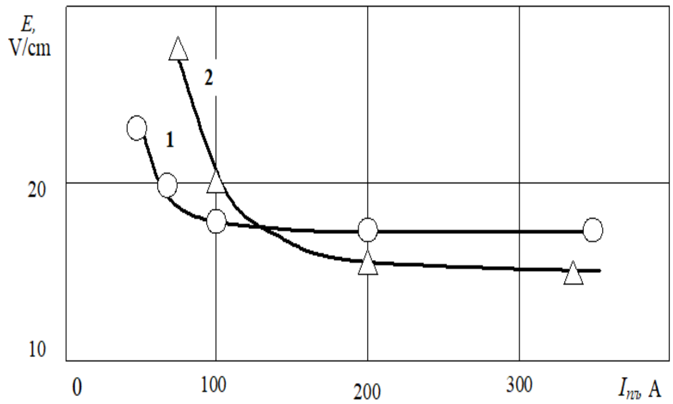

Figure 10: Dependence of the Electric Field Intensity of the Arc Column on the Current for the Plasma (1) and Stabilized Arc (2) (Dc = 8 Mm, Lc-I = 15 Mm, Lc = 6mm,Gпл.Г = 0.30 G/S).

The results of the performed experiments showed that the increase in the arc current to 100 A causes a sharp drop in the electric intensity of the plasma-arc column (Figure 10). In case of the increasing of the arc current, the electric field intensity in the arc column remains almost unchanged. There is the same dependence of the electric field intensity on the current for the stabilized arc, as shown in (Figure 10).In case of the reducing of the diameter of the molding nozzle and augmentation of the plasma gas flow, the electric field intensity of the plasma-arc column increases, as shown in (Figure.11).

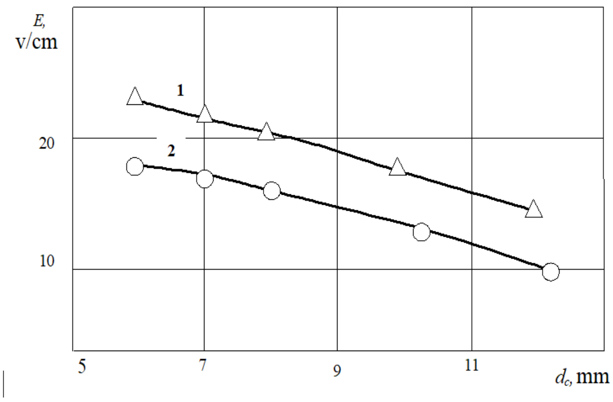

Figure 11: Dependence of the Electric Field Intensity of the Arc Column on the Diameter of the Molding Nozzle At Different Values of the Plasma-Forming Gas Flow: 1 - $G_{пл.Г}$ = 0.89 G/S; 2 - $G_{пл.Г}$= 0.33 G/S; ($I_{пл}$= 200 A, $L_{с\text{-}И}$= 15 Mm).

The dependence of the electric field intensity of the arc column on the length of the arc gap $L_{с\text{-}и}$ was analyzed. The result of the analysis is shown in (Figure. 12). The analysis revealed that the intensity *E* for a constricted plasma-arc under ($L_{с\text{-}и}$<12) mm practically changes, and the arc in this range has a cylindrical shape. Due to the conical shape of the stabilized arc, its intensity *E* decreases as the distance from the nozzle section to the product increases. If a wire is introduced into the plasma-arc, then the electric field intensity of the arc column increases. Due to the cooling effect of metal vapors [16], the electric field intensity of the arc column is higher when the intensity *E* is measured under the wire than when it is measured over the wire and makes, respectively, 2.3 and 3.0 V/cm under $I_{пл}$=200 A, d_c = 8 mm, $L_{с\text{-}и}$ = 25 mm.

The magnitude estimations at the electrode voltage drops on the product under the direct and inversed polarity of the plasma-arc are shown in figure.13, the curve U_o=$f(L_{пл})$ has a dropping section on the section of currents up to 100 A, and there is a clearly defined linear section under large values of the currents. Anode voltage drop is almost independent from the arc current. Electrode voltage drops in the arc discharge changes the electrode voltage drops of the plasma discharge versus current.

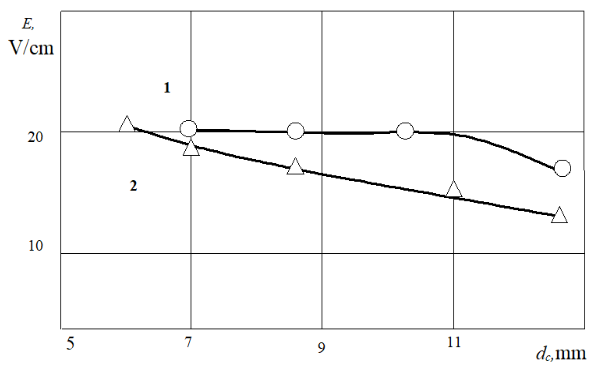

Figure 12: Dependence of the Electric Field Intensity of the Arc Column on the Length of the Arc Gap: 1 — Plasma-Arc; 2 — Stabilized Arc ($I_{пл}$= 200 A, D_c = 8 Mm, $G_{пл.Г}$= 0.89 G/S.)

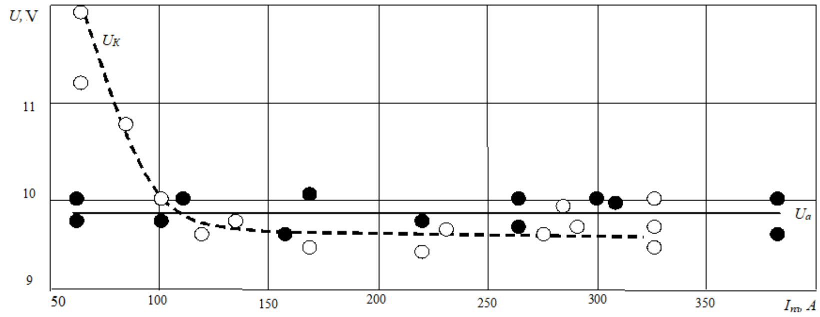

Figure 13: Dependence of the Near-Electrode Voltage Drops on the Plasma-Arc Current in CO_2 (D_c = 8 Mm, $L_{c\text{-}И}$= 18 Mm, $G_{пл.Г}$= 0.20 G/S).

The experiment results of measuring the radial dimensions of the plasma-arc depending on the parameters of the mode and the construction of the torch are shown in (Figure. 14 – 16).

Figure.14 shows the dependence of the diameter of the plasma-arc column on the diameter of the molding nozzle at different plasma gas flow. Figure.15 shows the dependence of the diameter of the conductive channel of the arc column on the plasma-arc current. Figure. 16 show the dependence of the diameter of the conductive channel of the arc column on the length of the arc gap.

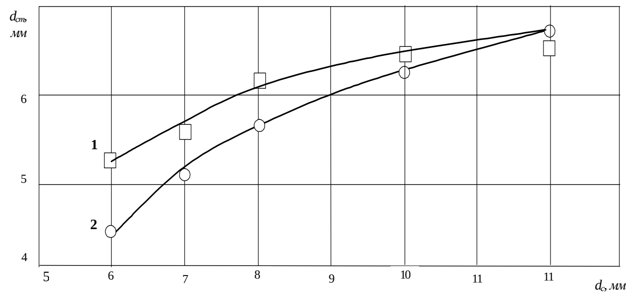

Figure 14: Shows the Dependence of the Diameter of the Conductive Channel of the Arc Column on the Diameter of the Molding Nozzle at Different Plasma Gas Flow: 1 - $G_{пл.Г}$ = 0.36g/S; 2 - $G_{пл.Г}$= 0.89 G/S. (Straight Polarity $I_{пл}$ = 200 A, Distance of the Probing Plane From the Nozzle is 8.5 Mm, $L_{пл}$= 23mm.

The experimental results revealed that the cylindrical shape is established when the electric field intensity and the plasma temperature remain unchanged along the column.

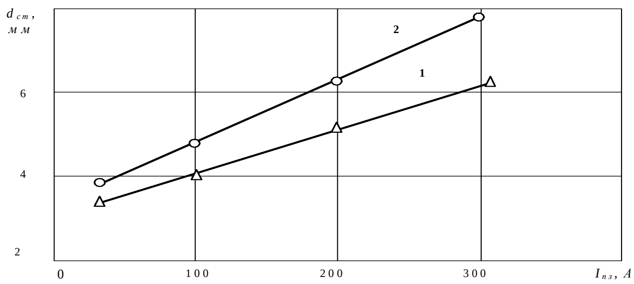

Figure 15: Dependence of the Diameter of the Conductive Channel Of the Arc Column On the Plasma-Arc Current: 1 - Constricted Arc; 2 - Stabilized Arc ($L_{c\text{-}И}$= 15mm, D_c = 8 Mm, $G_{пл.Г}$ = 0.89 G/S.)

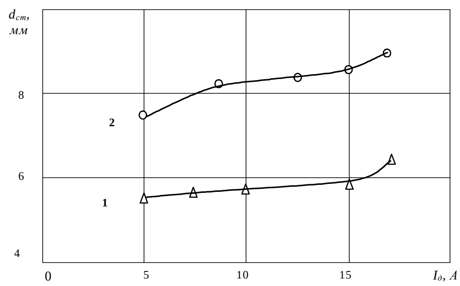

Figure 16: Dependence of the Diameter of the Conductive Channel of the Arc Column on the Length of the Arc Gap: 1 - Constricted Arc, 2 - Stabilized Arc ($I_{пл}$= 200 A, D_c = 8 Mm, $G_{пл.Г}$ = 0.89 G/S).

If an axial gradient of the field and temperature exists, then the arc column has a shape of a cone. The diameter of the axial zone in the arc constricted by the plasmatron channel is determined by the arc current and the parameters of the plasma gas. The peripheral zone prevents the bypassing of the arc by the walls of the nozzle scale. The axial zone of the arc behaves similarly to a solid body and constrict slightly under the action of the gas flow. The diameter of the axial zone depends on the arc of the current. When the plasma-arc current increases, the diameter of its column increases, both the stabilized arc and for the constricted arc is shown in (Figure. 15). Studies on the dependence $dcm=f(L_{c\text{-}u})$ showed that for the constricted arc, the shape of the arc column remains cylindrical almost to $L_{c\text{-}u}$= 15m. If the length of the arc gap increases, the diameter of the arc column will also increase, the stabilized arc will have the shape of a cone, because a marked increase in the diameter of the arc column occurs with the increase of the arc length (Figure. 16).

The relevance of the study is as follows. It leads to the conclusion that during the formalization of welding parameters, the methods of the fuzzy set theory [17], the decision models [18] and the methods of the theory of possibilities should be applied [19]. The synthesis of welding control system should be performed as the synthesis of a hybrid control system [20].

4. CONCLUSIONS

In this paper, experimental research is characterized by a strict approach to obtaining statistical data and their processing. The statistical data processing is represented as volt-ampere characteristics of plasma arc in gas, under different arrangements of the plasma arc welding process performance, during the plasma arc exploration, dependence of the electric field of arc column intensity on the current, dependence of diameter of the arc column current conducting channel on the former nozzle diameter. All these dependencies represent abundant material for estimating acceleration characteristics for further synthesis of the systems for automatic control of the plasma arc welding process. The system of automatic control of the welding process can be represented as a system of the volt-ampere arc control. Since the volt-ampere arc has its own physical characteristics, the control is aimed at maintaining (adjustment) of these characteristics depending on the assigned task of welding.

Accordingly, if the welding control system is implemented as a state-based control system, then the states of the automatic control system can use several parameters, for example, concentration of heat flow, gas-kinetic pressure on the pool, plasma-arc length and other parameters, which determines the processing characteristics of the welding process, can be taken as the states of the automatic control system. Anyhow, in the context of development of the present paper, it

should be noted that the welding process is influenced by agitations, which is rather difficult to find precise mathematical models for – e. g, influence of heat conductivity of plasma gas. In the result, the characteristics (graphical dependencies of the volt-ampere arc) represent numerous acceleration characteristics. The automatic control system must be adapted for the agitations, which are a different trend of research.

Practicality of the above research consists of the following. We can obtain plenty of acceleration characteristics to synthesize controller of the automatic control system and establish correlation between their type and parameters of the welding process (including agitations). After that, the parameters and the welding process are formalized with the use of methods of the fuzzy set theory, decision-making models and the theory of opportunities. Synthesis of the system of welding automatic control shall be performed as a synthesis of the hybrid control system.

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